

# The MAXI Mission on the ISS: Science and Instruments for Monitoring All Sky X-Ray Images

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## Abstract

The Monitor of All Sky X-ray Image (MAXI) mission is the first astronomical payload to be installed on the Japanese Experiment Module - Exposed Facility (JEM-EF or Kibo-EF) on the International Space Station (ISS). It is scheduled for launch in the middle of 2009 to monitor all-sky X-ray objects on every ISS orbit. It will be more powerful than any previous X-ray All Sky Monitor (ASM) payloads, being able to monitor hundreds of Active Galactic Nuclei (AGNs). A realistic simulation under optimal observation conditions suggests that MAXI will provide all sky images of X-ray sources of  $\sim 20$  mCrab ( $\sim 7 \times 10^{-10}$  ergs cm<sup>-2</sup> sec<sup>-1</sup> in the energy band of 2-30 keV) from observation on one ISS orbit (90 min),  $\sim 4.5$  mCrab for one day, and  $\sim 2$  mCrab for one week. The final detectability of MAXI could be  $\sim 0.2$  mCrab for two years, which is comparable to the source confusion limit of the MAXI field of view (FOV). The MAXI objectives are (1) to alert the community to X-ray novae and transient X-ray sources, (2) to monitor long-term variabilities of X-ray sources, (3) to stimulate multi-wavelength observations of variable objects, (4) to create unbiased X-ray source catalogues, and (5) to observe diffuse cosmic X-ray emissions, especially with better energy resolution for soft X-rays down to 0.5 keV.

MAXI has two types of X-ray slit cameras with wide FOVs and two kinds of X-ray detectors consisting of gas proportional counters covering the energy range of 2 to 30 keV and X-ray CCDs covering the energy range of 0.5 to 12 keV. Both cameras scan all-sky X-ray images twice due to two different directional cameras every 90 minutes synchronized with the ISS orbit. The data are sent through the downlink between the ISS and a ground station via data-relay satellites. MAXI will thus enable us to report X-ray novae or transients to astronomers worldwide within a few minutes. The ground-based nova-alert system rapidly reports these events with 0.1 to 0.2 degree position accuracy to astronomers worldwide for further follow-up observations. Measurements of each source are combined on the ground. As a result, we will be able to detect even a weak source such as an AGN. MAXI is capable of creating source catalogues for specific periods to investigate the variabilities of X-ray sources.

**Key words:** ASM, All Sky Monitor, X-ray nova, AGN, GRB, X-ray transient, X-ray source catalogue

## 1. Introduction

The All Sky Monitor (ASM) for X-ray observations has a long history (Holt and Priedhorsky 1987). The ASM on Ariel 5 (a British satellite) was the first dedicated pioneer payload to observe X-ray novae and transients (Holt 1976). The Ariel 5 ASM, which has two sets of one-dimensional scanning pinhole cameras, discovered several novae and transient X-ray objects. Thereafter, the terms "X-ray nova" and "X-ray transient" have become well-known in X-ray astronomy. X-ray instruments with a wide field of view (FOV) as well as ASM can not only detect X-ray novae and transients, but also monitor long-term X-ray variabilities of X-ray sources (Priedhorsky and Holt 1987).

Although Vela A & B satellites with a wide FOV discovered the first gamma-ray burst (GRB) before the Ariel-ASM (Klebesadel et al. 1973), those detectors were not much suitable for monitoring GRBs as well as X-ray novae and transients. Subsequently, dedicated GRB monitors confirmed that a considerable number of mysterious GRBs are produced in the universe. GRB monitors with a wide FOV have advanced greatly since a wide field camera on Beppo-SAX discovered a GRB afterglow (Costa et al. 1997). Since then, special GRB satellites such as HETE-2 (Ricker et al. 2002; Shirasaki et al. 2004) and Swift (Gehrels et al. 2004) have been realized.

The ASM, however, advanced gradually as a supplemental payload. Ariel-ASM with pin-hole cameras operated successfully for seven years with the main payload which made spectrum observations of bright X-ray sources (Holt 1976). In 1987 the ASM on the Japanese satellite Ginga (Tsunemi et al. 1989) succeeded the Ariel-ASM. Ginga-ASM was able to observe the spectra of X-ray novae as it scanned the sky from 60 degrees through 360 degrees once every day with multi-slat collimators. Ginga-ASM greatly advanced the science of black hole binaries with the discovery of nova-like black hole binaries (Tsunemi et al. 1989; Kitamoto et al. 1992; Kitamoto et al. 2000). Ginga-ASM was operated successfully for 4.5 years, and some of transients discovered by ASM were observed in detail by the main large area counters on Ginga (Turner et al. 1989).

Since 1996, RXTE-ASM (a NASA satellite) has monitored known X-ray sources in addition to X-ray novae and transients (Levine et al. 1996). Systematic long-term data of Galactic variable sources provide quasi-periodic properties of the accretion disc (Zdziarski et al. 2007a; 2007b). RXTE-ASM has provided much useful data for X-ray variable sources for 13 years, but the detection limit is around 10 mCrab. Therefore, the main targets of RXTE-ASM were the Galactic X-ray sources of which monitoring was suitable for performing detailed observations of these targets with an RXTE prime instrument, a large-area proportional counter array (Remillard and McClintock 2006).

Now we have long term light curves for bright X-ray

sources from the above three ASMs. Some sources revealed periodic or quasi-periodic component of long time scale with combined analysis over the last 30 years (Paul et al. 2000). Future ASMs taking over the three ASMs can continue to investigate further long-term behaviour of X-ray sources. Although the above three ASMs have been in operation, they cannot adequately monitor AGNs because of their low sensitivity. Thus far, Galactic X-ray novae and transients data have been accumulated although the information is not completely clear. No long term variability of AGN has not been observed with sufficient data. Therefore, the most important role for future ASMs is to better the detection limit for AGN monitoring. Considering this historical situation, MAXI was proposed as a payload of ISS (Matsuoka et al. 1997). It will be one of the ASMs responsible for AGN monitoring. A slit hole camera with a large detection area meets this requirement. Since MAXI has a composite structure of slit holes and slat collimators without a mirror system, the angular resolution is not good (i.e., the FWHM of slat collimators is 1.5 degrees), but the localization accuracy can be 0.1 degree for the sources of enough statistic (e.g., bright sources and sources with enough counts accumulated for optimum time). A mirror-type ASM, such as the Lobster-eye ASM, is promising for the future although its energy band is limited to soft X-rays (Priedhorsky et al. 1996).

The MAXI to be attached to the Japanese Experiment Module (JEM; Kibo) on the ISS is ready to be launched. In this paper we will present an overview of MAXI and the new scientific contributions expected of it. The first part of this paper will discuss the astronomical science expected of MAXI. The second part will describe the MAXI instrumentations, and observational simulation.

## 2. Key Science

The MAXI mission enables the investigation of ASMs and surveying. MAXI will alert astronomers of GRBs, X-ray novae, and flare-up increases of X-ray sources if they occur. Long-term data of X-ray sources will enable us to determine a special time scale of variability, e.g., long-term periodic or quasi-periodic motions of X-ray sources. MAXI can promote multi-wavelength observation in collaboration with other space and ground observatories such as X-ray, infrared, and optical satellites, radio, and optical ground observatories. MAXI systematic observations of the variable activity of black hole binaries and AGNs are used to investigate how and where they produce their variable activities.

MAXI provides unbiased X-ray source catalogues over all the sky. Monthly or biannual X-ray catalogues could contribute to the long-term study of variable behavior of AGN for the first time. A catalogue accumulated for two years could provide all-sky AGNs corresponding to a moderately deep survey to the entire sky. This unbiased AGN catalogue will far surpass the investigation of the distribution and evolution of AGNs for the HEAO-1 A2 catalogue which has been utilized for long time (Piccinotti et al. 1982). MAXI is also able to make an all sky X-ray map

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with soft X-rays and medium energy X-rays. The soft X-ray map provides line features such as Oxygen X-ray lines, which are useful in researching geo-coronal recombination lines (Fujimoto et al. 2007) as well as the evolution of hot gas in the Galaxy (McCammon and Sanders 1990; Tanaka and Bleeker 1977).

Current Swift (Gehrels et al. 2009; Burrow 2009) and INTEGRAL (Ubertini et al. 2009) satellites with wide FOVs of hard X-ray detectors have provided X-ray source catalogues including AGNs in addition to a considerable number of transients. Since these results are complementary to those of MAXI, it could be promising to science that these three ASM missions will operate simultaneously. Furthermore, the recently developed gamma-ray large-area space telescope, the Fermi Gamma-Ray Space Telescope (Abdo et al. 2008; Thompson et al. 2009), is a gamma-ray ASM with an energy band complementary to that of MAXI. All-sky images with both ASMs may reveal new information.

### 2.1. X-ray Novae and GRBs Alert

More than 90% of the black hole candidates are X-ray transients or novae (McClintock and Remillard 2007). In the last 20 years, 29 have been discovered, mostly with RXTE-ASM and partly with Ginga-ASM, while about 30% of them have been serendipitously discovered by pointing observatories (Negoro 2009). Thus far, observed X-ray novae are located near the Galactic center and near the solar system; i.e., their distances are within about 6 kpc. Distant X-ray novae appear weak, but MAXI could detect these weak sources, since it can observe X-ray novae from distant regions about three times as far. Thus, it is expected that the nova discovery rate may increase by one order of magnitude.

X-ray light curves with energy spectra of X-ray novae have provided instability and phenomena deviating from the standard accretion disc model (Tanaka and Shibazaki 1996). Data of both low and high luminosities have resulted in the creation of a new theory concerning accretion discs (Mineshige et al. 1994), but these samples are not enough. We also expect that MAXI could observe X-rays from classical novae. Multi-wavelength observations of classical novae could provide useful information about the bursting mechanism of classical novae. Although classical novae are faint and soft in X-ray band, the durations are of months to years (Mukai, Orio & Della Valle 2008). Thus MAXI could detect some of them.

Swift has discovered many GRBs and has consequently enabled us to make rapid follow-up observations of them. Nevertheless, the energy band of the Swift detector is 15 to 200 keV (Gehrels et al. 2002). MAXI can cover the soft X-ray band of GRBs, and this information is important to the understanding of X-ray rich GRBs and X-ray flashes. It is expected that the population of the X-ray rich GRB is comparable to that of the GRB with an ordinary energy band (Sakamoto et al. 2005). The instant FOV of MAXI is not large, MAXI will be able to detect 3.5 prompt emissions and 2.5 X-ray afterglows of GRB per year (Suzuki et al. 2009).

MAXI is also able to observe transient X-ray binary pulsars with high orbital eccentricity and transient low mass X-ray binaries with neutron stars. Furthermore, Anomalous X-ray Pulsars (AXPs) are still enigmatic objects that appear as Soft Gamma Repeaters (SGRs) with enormous flux during a short time (Nakagawa et al. 2009; Morii 2009). Considering the recent Swift discovery of a new SGR (Barthelmy et al. 2008; Enoto et al. 2009), we could even expect MAXI to detect additional SGRs with weaker flux. Thus, MAXI may reveal new frontier of AXPs (i.e., magnetars) by detecting numerous new magnetar candidates (Nakagawa et al. 2009). Recently, special interest concerning long type I X-ray bursts has arisen with rare events of carbon-fueled super bursts and helium-fueled intermediately long bursts. These bursts are promising in the investigation of the deeper neutron star envelope (Keek and in't Zand 2008; Keek et al 2008). MAXI may discover such rare occurrences of X-ray bursts.

### 2.2. Long-Term Variability of X-Ray Sources

Most X-ray sources with compact objects are variable, due to the instability of the accretion disc and other reasons. Periodic or quasi-periodic long-term variability is sometimes created from interaction between the accretion disc and the binary system. If there were a third object in the X-ray sources, we could expect some other periodicity in addition to binary period (Zdziarski 2007a). The third body might be useful for inspecting the accretion disc. However, no one has discovered such a triple-body system in the X-ray sources. A composite time scale of variability would help generate this knowledge and/or may create new knowledge. An unusual X-ray transient from the Galactic center region (Smith et al. 1998) is progressing in a new class of recurrent and fast X-ray transient sources (i.e., SFXTs). These transients sometimes occur in high-mass X-ray binaries associated with super-giant companions. It is promising for further investigation that MAXI in addition to INTEGRAL and Swift monitors these objects with a wide FOV (Ebisawa 2009; Ubertini et al. 2009). Generally, a time scale of AGNs variability is longer than that of X-ray binaries. The time scale of AGNs is useful in understanding a complicated structure around the AGNs. If some AGN had formed a super-massive binary black hole system, we could expect some periodic variation over a year's time (Hayasaki et al. 2008).

### 2.3. Multi-Wavelength Observations of Variable Objects

The knowledge of bursts, transients, and variable objects has progressed considerably with multi-wavelength observations. Research of GRB afterglows has advanced greatly as a result of rapid follow-up observations in X-ray, optical, and radio bands (Gehrels et al. 2006), but there are still just a few samples of short GRBs and X-ray rich GRBs. Coordinate observations of Blazars in radio, infra-red, optical, X-ray, and ultra-high-energy (TeV) gamma-rays have confirmed a Synchrotron Self-Compton (SSC) model for highly variable periods (Kubo et al. 1998; Kataoka et al. 1999; Takahashi et al. 2000). However, the emission mechanism of other AGNs as well as Blazars has

not yet been completely understood because of complicated correlations among multi-wavelength observations to help investigate this mechanism (Maoz et al. 2002). TeV gamma-ray observations by Čerenkov telescopes have progressed remarkably since TeV gamma-rays from some Blazars were detected (Petry et al. 1996; Aharonian et al. 1997). GeV gamma-ray observations by Fermi-GLAST are now available as an ASM (Thompson et al. 2009). MAXI can promote further simultaneous multi-wavelength observations of Galactic active objects as well as AGNs with gamma-rays (GeV & TeV) to radio bands (Fender 2009; Madejsky et al. 2009).

#### 2.4. Unbiased X-Ray Source Catalogues

Nominal beam size (i.e., angular resolution by FWHM) of MAXI is  $1.5 \times 1.5 \text{ deg}^2$ . It is estimated that a confusion limit of X-ray sources is  $5 \times 10^{-12} \text{ erg cm}^{-2} \text{ sec}^{-1}$  from recent Log N - Log S plot of X-ray sources (Ueda et al. 2003); i.e., 0.2 mCrab in the energy band of 2 to 20 keV. Thus, we can set a detection limit of 0.2 mCrab as an ideal goal, although the period of its achievement depends on intrinsic background and systematic error. To estimate observation time we conducted a realistic MAXI observational simulation. MAXI achieved a detection limit of 0.2 mCrab with a two-year observation (Ueda et al. 2009). Other simulations suggest that it is possible to detect 20 mCrab for one orbit (90 min.), 4.5 mCrab for one day, and 2 mCrab for one week (Hiroi et al. 2009; Sugizaki et al. 2009). Some regions in the sky are covered by a bright region from the Sun and are sometimes affected by the South Atlantic Anomaly (SAA). Therefore, detection sensitivities are estimated under the best condition. The detectability of MAXI is not uniform in the entire sky, but slightly depends on the direction. The MAXI simulation indicates that we can obtain 30-40 AGNs every week (Ueda et al. 2009). This sample is comparable to the number from HEAO 1-A2 (Piccinotti et al. 1982). We are also able to estimate about 1000 AGNs with two-year observations. MAXI observes those AGNs in a harder energy band than observed by ROSAT. Thus, MAXI could give an unbiased population ratio of Type I and Type II AGNs. Furthermore, if weekly or monthly catalogues are created, we can discover the intensity variability for a considerable number of AGNs. It is possible to detect a flare-up of Blazars and then follow their light curves. The time sequence of X-ray unbiased catalogues is very useful in researching the evolution of AGNs as well as their long-term variability. Here the next comment is noted. Although much deeper surveys of AGNs in the 2-10 keV band with ASCA (e.g., Ueda et al. 1999) and Chandra/XMM-Newton (Brandt & Hasinger 2005 and references therein) have presented Log N - Log S plots for researching the evolution of AGNs, they are limited to a small portion of the sky, and hence cannot constrain that of bright AGNs with small surface densities.

#### 2.5. Diffuse Cosmic X-Ray Emissions

The problem of the diffuse cosmic X-ray background (CXB) has a long history. A recent deep survey of X-ray

sources in a medium energy band of 2 to 10 keV (Ueda et al. 2003) suggests that the CXB may be due to the superposition of AGNs, as proposed theoretically (Morisawa et al. 1990). It is still unknown how some kinds of AGNs are distributed in the universe. A global CXB distribution is compared with that of optical AGNs and/or an infrared map. Thus we can investigate the evolution or emission mechanism of the all-sky AGN distribution. If we can obtain some difference of distribution in different energy bands, we can investigate the distribution of Type I and Type II AGNs.

The diffuse emission of soft X-rays less than 1 keV is attributed to geo-coronal gas as well as hot bubbles from supernova remnants (Tanaka and Bleeker 1977; McCammon and Sanders 1990). ROSAT obtained a precise all sky map with a broad energy band of soft X-rays. MAXI can also obtain all-sky maps of soft X-rays but with better energy resolution (e.g., resolving Oxygen K-line, and Neon K-line). Recent Suzaku observations revealed a strong contribution of recombination K-lines of Oxygen and Carbon in the geo-coronal region (Fujimoto et al. 2007). MAXI is able to observe the Oxygen line with seasonal variation and solar activity. Therefore, MAXI observations make it possible to discriminate between the contribution of geo-corona and that of supernova remnants. Thus, we could investigate geo-coronal science as well as element-evolution of supernova remnants from soft X-ray line observations.

### 3. MAXI Project

The large-scale Space Station (SS) project started in 1985 with the collaboration of the USA, Japan, Canada, and the European Space Agency (ESA). Planning of the JEM was also initiated at that time. In 1995, Russia began to take part in the SS project. The project was subsequently reduced to its present scale and then renamed the International Space Station (ISS). JEM planning and designing have continued, but actual construction and basic tests of the engineering model began at that time. JEM consists of a pressurized module for micro-gravity experiments and an exposed facility (EF).

ISS rotates synchronously in its orbit so that one side always points towards the center of the Earth and the opposite side views the sky. Therefore, the sky side of JEM-EF surveys a great circle every ISS orbit. Themes for JEM-EF include the space science payload for astrophysics and Earth observations, and space technology experiments such as robotics. However, JEM-EF does not provide a perfectly stable platform because of unknown factors of some attitude fluctuation. Payload size and weight are limited to the capacity of the JEM-EF. A payload can be suitable for survey observation, but not for pointing. Although a considerably wide FOV is available, the ISS structure and solar paddle partially block the view of JEM-EF. Since the ISS carries various experimental instruments and payloads, each instrument and payload has to accommodate many interfaces. Resources such as communication and power for each experiment or payload are



**Table 1.** Specification of MAXI slit cameras

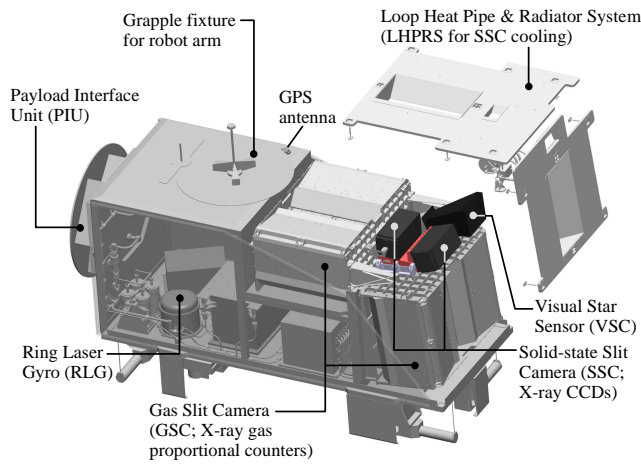
	GSC <sup>†</sup> : Gas Slit Camera	SSC <sup>†</sup> : Solid-state slit camera
X-ray detector	12 pieces of one-dimensional PSPC; Xe + CO <sub>2</sub> 1 %	32 chips of X-ray CCD; 1 square inch, 1024x1024 pixels
X-ray energy range	2–30 keV	0.5–12 keV
Total detection area	5350 cm <sup>2</sup>	200 cm <sup>2</sup>
Energy resolution	18 % (5.9 keV)	≤ 150 eV (5.9 keV)
Field of view*	1.5 × 160 degrees	1.5 × 90 degrees
Slit area for camera unit	20.1 cm <sup>2</sup>	1.35 cm <sup>2</sup>
Detector position resolution	1 mm	0.025 mm (pixel size)
Localization accuracy	0.1 deg	0.1 deg
Absolute time resolution	0.1 msec(minimum)	5.8 sec(nominal)
Weight <sup>‡</sup>	160 kg	11 kg

Notes.

\* FWHM × Full-FOV.

‡ MAXI total weight: 520 kg.

. SSC consists of two camera units, SSC-Z and SSC-H.

**Fig. 1.** Overview of MAXI; major subsystems are indicated.

also limited.

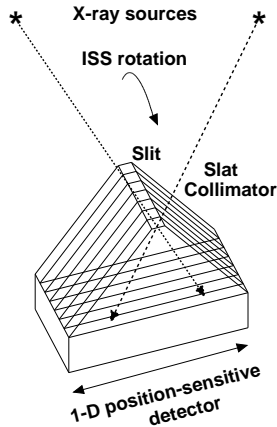
Considering these problems MAXI was proposed and finally accepted in 1997 by the National Development Space Agency of Japan (NASDA), now known as the Japan Aerospace Exploration Agency (JAXA). Thus, MAXI is the first astronomical payload for JEM-EF on the ISS. Although the launch was scheduled for 2003, the space shuttle, Columbia accident, and the ISS construction delay resulted in the postponement of the MAXI launch by several years. MAXI science instruments consist of two types of X-ray cameras, the Gas Slit Camera (GSC) and the Solid-state Slit Camera (SSC). These instruments and the support instruments on the MAXI payload are shown in Figure 1, and their characteristics are listed in Table 1. The support instruments consist of a Visual Star Camera (VSC), a Ring Laser Gyroscope (RLG), a Global Positioning System (GPS) and a Loop Heat Pipe and Radiation System (LHPRS). The VSC and the RLG determine the directions of the GSC and the SSC as precisely as a few arc-seconds every second. The GPS at-

taches the absolute time as precisely as 0.1 msec to GSC photon data. The LHPRS is used for heat transportation and heat radiation from thermo-electric coolers (Peltier elements) to cool the CCD.

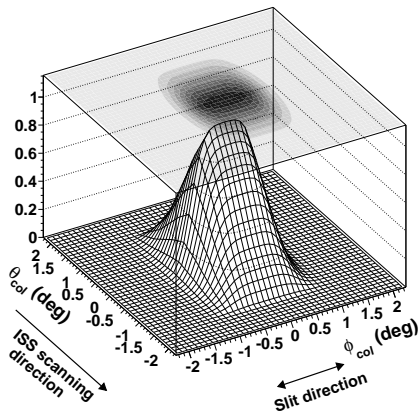
The main role of the GSC is to perform as the X-ray ASM, which has the best detectability than previous ASMs have for a time scale longer than hours. All sky X-ray images obtained by GSC are also useful for new X-ray variable catalogues. On the other hand the main mission of SSC is to make all sky X-ray maps for extended sources with better energy resolution than ROSAT maps, although the detection area and live time for discrete sources are less by 1/20 than those of GSC. We also expect to detect the transients in soft X-ray band although the detectability of transients with SSC is also poorer by 1/20 than that of GSC.

MAXI will be carried by the Space Shuttle, Endeavour, along with the JEM (or Kibo)- EF from Kennedy Space Center in the middle of 2009. MAXI will finally be mounted on JEM-EF within two weeks of Endeavour launch. At that time all of Kibo's modules will have been installed on ISS. After the basic arrangement of the structure and infrastructure of JEM, MAXI will conduct performance tests for about three months. MAXI has a nominal lifetime of two years, but the expected goal is five or more years to achieve long-term monitoring.

MAXI data will be down linked through the Low Rate Data Link (LRDL; MIL1553B), and the Medium Rate Data Link (MRDL; Ethernet). MAXI is operated through the Operation Control System (OCS) at Tsukuba Space Center (TKSC), JAXA. MAXI data are not only processed and analyzed at TKSC, but they are also transferred to the Institute of Physical and Chemical Research (RIKEN) MAXI data facility. General users of MAXI can request the scientific data from RIKEN (a main port) as well as from JAXA (a sub-port) whenever they desire. To search where X-ray novae, transients, or flaring phenomena appear suddenly in the sky we will conduct automatic data analysis at TKSC by using down linked data



**Fig. 2.** A principle of MAXI Slit Camera; it consists of slit & slat collimators and one-dimensional position sensitive X-ray detector.

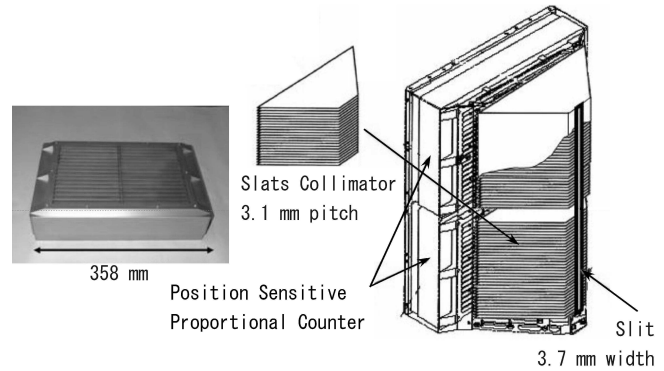


**Fig. 3.** Typical sample of PSF (Point Spread Function); a slat collimator has a triangular response (ISS scanning direction), while a slit collimator has a trapezoidal response (Slit direction corresponding to  $\beta$  in Fig.6).

from LRDL. If such a source is discovered, we will report this event to astronomers and dedicated users worldwide via the Internet from TKSC. This nova alert system has been developed to achieve automatic alert (Negoro et al. 2008). The MAXI team will also maintain archival data at RIKEN using the data from LRDL and MRDL, such as all sky X-ray images, X-ray light curves, and spectra of dedicated X-ray sources. In principle all astronomical data of MAXI will be available for public distribution (Kohama et al. 2009).

#### 4. X-ray Mission Instruments

A specific object is observed by MAXI with a slit camera for a limited time with every ISS orbit. The X-ray detector of the camera is sensitive to a one dimensional image through the slit, where the wide FOV through the slit spans the sky perpendicular to the ISS moving di-



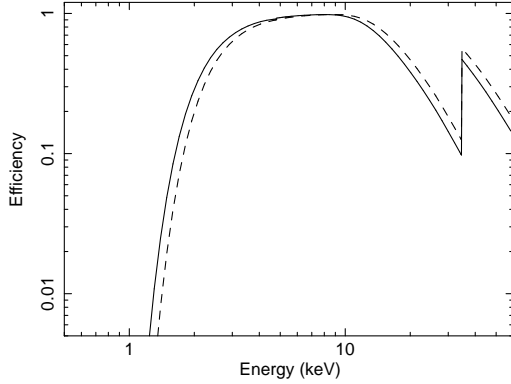
**Fig. 4.** The GSC unit and a gas-proportional counter; the unit consists of two gas-proportional counters, slit and slat collimators.

rection as shown in Figure 2. The scanning image of an object is obtained with the triangular response of a slat collimator according to ISS movement. An intersection of the slit image and the triangular response image corresponds to a source location in the sky as a Point Spread Function (PSF). This is shown in Figure 3.

Objects located along a great circle stay for 45 sec in the FOV of MAXI cameras, where the time of stay is the shortest in the MAXI normal direction (for a great circle). For objects in the slanted field from the great circle, they achieve slightly longer observation. Any target will come repeatedly in each field of the horizontal and zenithal cameras with every ISS orbital period. In this situation MAXI can intermittently monitor a short time scale variability for bright X-ray sources such as X-ray pulsars and low mass X-ray binaries. It can monitor their variability of weak sources on a time scale of 90 min or longer if we integrate the data. MAXI has two types of X-ray cameras: the GSC and the SSC which are described in the following sub-section.

##### 4.1. Gas Slit Camera (GSC)

GSC is the main X-ray camera and consists of six units of a conventional slit camera as shown in Figure 1 and Table 1 (Mihara et al. 2009). The GSC unit consists of two one-dimensional proportional counters (produced by Oxford Instruments Co. in Finland), and slit & slat collimators as shown in Figure 4. Thus, twelve proportional counters have a  $5350 \text{ cm}^2$  detection area in total. Each counter has six cells of resistive carbon wires that are guarded by a veto-detector region in the bottom and on both sides (Mihara et al. 2001), while the carbon wire divides the charge from the signal into both terminals for one-dimensional determination. The X-ray detection efficiency of the proportional counter (Xe 1.4 atmospheres with 1 %  $\text{CO}_2$ ) is plotted against X-ray energy in Figure 5. Observational energy band of GSC is set to be 2-30 keV in standard operation mode where the detection efficiency for X-rays in this band is above 10 % as seen in Figure 5. The observation above Xe K-edge of 34.6 keV is possible as a special mode by adjusting amplifier gain and high

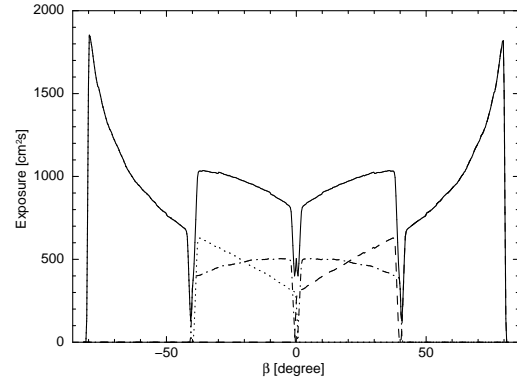


**Fig. 5.** X-ray detection efficiency of MAXI proportional counter for energy; a solid line indicates the efficiency for normal incident X-rays, while a dashed line indicates that of incident X-rays from 40 degrees.

voltage. Although a response function above Xe K-edge is complicated due to escape peak, the test for this function has been done using synchrotron X-ray beams. The slat collimator response is 3.5 degrees in bottom-to-bottom, and a slit image corresponds to 1.5 degrees covering a wide field between  $-40$  degrees and  $+40$  degrees. The proportional counters detect incident X-ray photons from vertical to  $\pm 40$  degree slant direction.

Two FOVs of GSC-H and GSC-Z are placed in horizontal (forward) and zenithal directions to compensate when the sky is unobservable to one FOV or the other (due to high radiation background, such as SAA). The FOV of one camera is 80 degrees. Two camera units can cover 160 degrees, but the FOV of each central camera of GSC-H and GSC-Z overlaps with each half of the FOV of both side cameras to even the exposures as shown in Figure 6 which shows the product of effective area and dwell time according to one orbit scan. The exposure time per orbit depends on the direction of a star by a factor of  $1/\cos\beta$ , where  $\beta$  is the angle of the star slanted from scanning a great circle. Both edges of 10 degrees in this figure are omitted, due to the shadow of the ISS structure, where the scanning loss is 1.5%. The forward FOV is tilted up by 6 degrees so as not to observe the Earth even when the ISS attitude changes. Thus, the FOV of GSC-H can scan the sky with ISS rotation without Earth occultation. By making the observation time longer than 90 min, we made the instrument simpler, and then optimized it to search in the AGN discovery space for the longer-term AGN variability ( $> 1.5$  hour).

Considering this directional performance, we conducted various laboratory tests of all proportional counters. Here we explain some of the results. The position resolution was tested at every 2 mm segment of two-dimension on the incident window for all proportional counters. The data were taken using 0.1 mm pencil X-ray beams with X-ray energies of 4.6, 8.0, and 17.4 keV. The total length of the carbon anode wire is 32 cm; thus, the total resistance is 31 to 37 k $\Omega$ . The difference of resistance depends on the slight difference of wire diameters. The energy



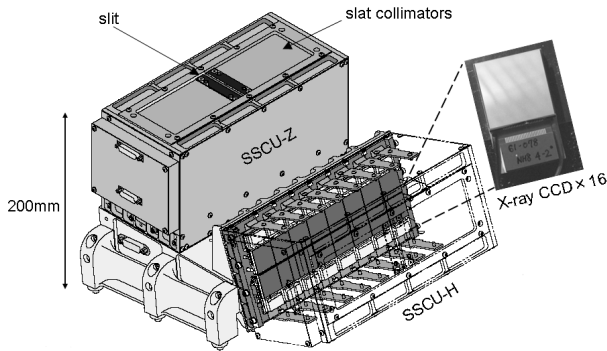
**Fig. 6.** A solid line shows the total product of effective area and dwell time according to one orbit scan for a point source for the angle ( $\beta$ ) slanted from scanning a great circle. This value is common to GSC-Z and GSC-H. A chain line indicates the contribution of a central GSC unit only, while a dashed line and a dotted line are those of a right side GSC unit and a left side GSC unit only, respectively.

response also differs for different anode wires. We took comprehensive data useful for energy response and position response (Mihara et al. 2001; Isobe et al. 2004). We also took the slat collimator response data using X-ray pencil beams (Morii et al. 2006). The data-base, including all these data, is regarded as the response function at the time of data analysis. In actual data analysis we will use each response function for the two dimensional surface of all carbon wires. Pulse height response depends on X-ray energy, where hard X-rays suffer the effect of anomalous gas amplification (Mihara et al. 2001).

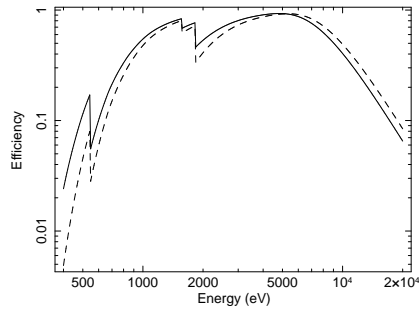
The simultaneous background for a localized source is measured in two regions separated from the source on the same detector in the FOV direction. Another background is measured in two regions just before and after observing the source on the scanning path, where the two regions are separated from the source. In this case, both measurement locations of the background on the detector are the same as the measurement location on the detector of the source. The background is employed if there are no appreciable sources in these directions. In addition, intrinsic background is necessary to obtain the cosmic diffuse background. The intrinsic background is gradually changing on orbit and for time even in the same direction (Hayashida et al. 1989). There is the small portion covered by a window frame of each detector in which cosmic diffuse X-rays as well as source X-rays are never irradiated. A small portion of the North Pole direction is also shadowed by ISS structure. Although these intrinsic background count rates are not enough to measure for instant time, the data accumulated for days or more could be used to make a reasonable model of intrinsic background as obtained for Ginga proportional counters (Hayashida et al. 1989).

#### 4.2. Solid-state Slit Camera (SSC)

Each unit of SSC-H/Z consists of 16 CCDs, where each CCD acts as a one dimensional position sensitive detector



**Fig. 7.** SSC consisting of a horizontal SSC (SSC-H) and a zenithal SSC (SSC-Z) and a CCD chip is depicted separately.



**Fig. 8.** X-ray detection efficiency of MAXI CCD for energy; solid line is the efficiency for a normal incident X-ray, while a dashed line indicates that for X-rays incident from 40 degrees.

for the slat collimator and the slit hole similar to the GSC system presented in Figure 1 and Table 1 (Tomida et al. 2009). The SSC-H camera is tilted up 16 degrees so as not to view the upper atmosphere. The response of the slat collimator scanning direction is 3 degrees for bottom-to-bottom, while a slit image corresponds to 1.5 degrees covering a wide FOV of 90 degrees as shown in Figure 7. One orbit scan of the SSC corresponds to 90 degrees x 360 degrees. Thus, it takes SSC 70 days to scan the entire sky depending on the precession of the ISS orbital plane, except for the bright region around the Sun. Thus, SSC will acquire actual all sky images every half year.

The X-ray CCD chip of SSC is produced by Hamamatsu Photonics K.K.. The CCD depletion layer is about 70  $\mu\text{m}$ , of which the X-ray detection efficiency is indicated in Figure 8. The observation energy band of SSC is set to be 0.5-12 keV in standard mode, but observations above 12 keV are possible in a special mode. However, since SSC is characterized by a low energy band, the energy band may be slightly shifted to lower energy than 0.5 keV, depending on the temperature for thermal noise. The CCD with 1024x1024 pixels, and a pixel size of 24  $\mu\text{m}$  x 24  $\mu\text{m}$  is a two-dimensional array, but SSC requires only one-

dimensional position information. Hence, multiple rows are summed in a serial register at the bottom of the imaging region, and the summed charges in the serial register are transferred to a read-out node. Eight, 16, 32 or 64 summed rows can be selected in normal observation by commands. The larger this number, the better the time resolution, and the better the angular resolution in the X-ray sky map.

The CCD is sensitive to particle radiations, but an irradiation test of the simulated radiation belt fluence suggests that the CCD can survive for the expected three-year mission (Miyata et al. 2003). Furthermore, it is possible to inject charges in the CCD before it becomes damaged due to irradiation (Miyata et al. 2003). Charge injection effectively restores the degraded performance of X-ray CCDs (Tomida et al. 1997).

To achieve better energy resolution with a CCD, all CCDs are cooled to -60 degrees C using thermo-electric coolers (Peltier devices) and the LHPRS. The maximum power of the thermo-electric cooler is 1 W/CCD. The LHPRS can automatically transfer heat from the Peltier device and emit heat from the radiation panel. Performance tests in the laboratory have been conducted with satisfaction (Miyata et al. 2002; Katayama et al. 2005). The nominal energy resolution width of X-ray spectra is 150 eV for Mn K X-rays (5.9 keV).

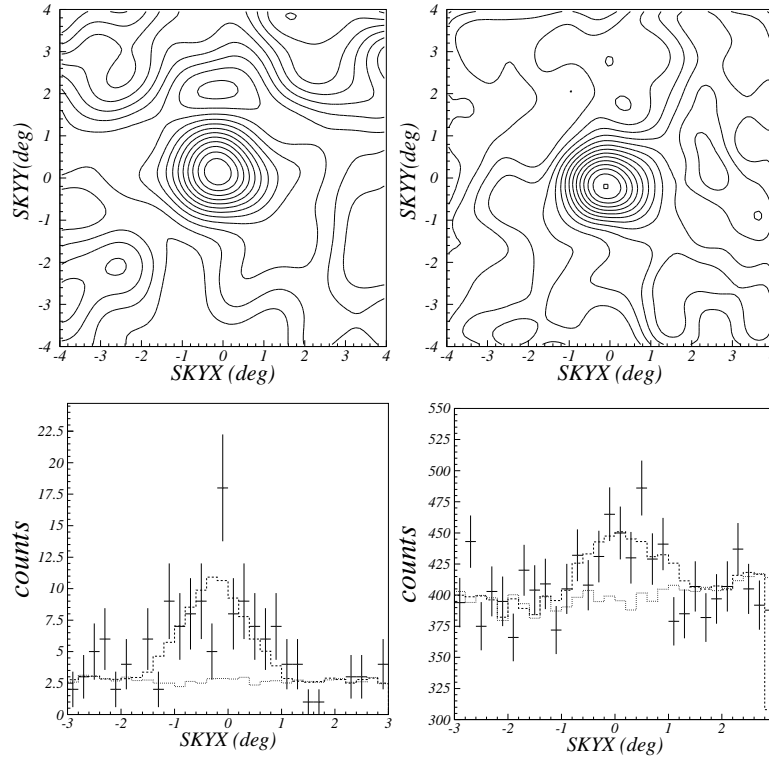
#### 4.3. Support Sensor

Since the ISS has a huge structure of  $\sim 108$  m and  $\sim 420$  tons, the attitude determined in a certain part of the ISS may be slightly different from that in a distant part, due to shaking of the structure. MAXI is designed to determine a target location as precisely as less than 0.1 degree. Thus, it is necessary to determine the attitude of the MAXI coordinate by less than 0.1 degrees every time. For this purpose, MAXI itself has a VSC and an RLG. The VSC can observe three or more stars, and it can determine a MAXI coordinate by 0.1 arc minute. When the VSC is not available for measurement due to solar radiation, the RLG will extrapolate the attitude from a certain result of the VSC to the following result. This attitude determination is performed automatically by onboard software including a Kalman filter on the MAXI data processor (Ueno et al. 2009; Horike et al. 2009).

The high voltage of a proportional counter of GSC will be reduced to 0 volt when solar radiation or SAA radiation is extremely strong. The command signal for this reduction will be issued by working of the Radiation Belt Monitor (RBM). This high voltage reduction is also useful for setting program commands in advance because of the possible prediction of solar position and SAA location.

The time precision of photon acquisition from GSC is 0.1 msec by referring to GPS signal. This precise absolute time is used for milli-second pulsars and burst acquisition analysis. Thus, only one GPS is installed in MAXI for precise time reference without unknown lag. However, the time resolution of SSC is 5.8 sec in the normal observation mode.



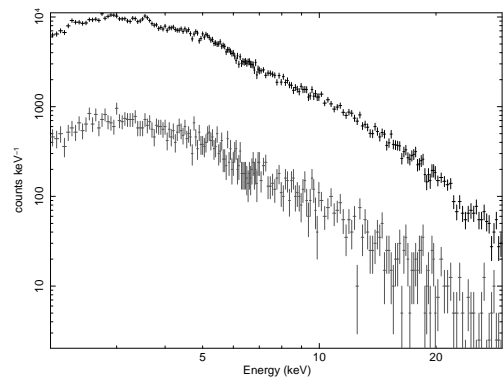


**Fig. 9.** (a) Simulation is used to detect a source of 20 mCrab for one ISS orbit. Contours are smoothed in the upper panel, while a cut figure through a peak is indicated with data points in the lower panel. (b) Simulation is used to detect a source of 2 mCrab in one week. Contours are smoothed in the upper panel, while a cut figure through a peak is indicated with data point in the lower panel.

## 5. MAXI Simulation and Expected Performance

A realistic simulation has been conducted with the recently developed MAXI simulator, which generates fully simulated data of MAXI instruments on the ISS (Eguchi et al. 2009). The simulator takes into account various conditions on the ISS, i.e., the occultation of the sky with solar panels, particle and intrinsic background, and response function of X-ray cameras. The attitude data and absolute time are attached to each event data on the ground. Thus, we can plot each event with energy information in a certain direction in the sky. Integrated events from a certain direction for a certain time correspond to intensity, including background from the direction. Here we demonstrate some of the simulated results (Hiroi et al. 2009; Sugizaki et al. 2009).

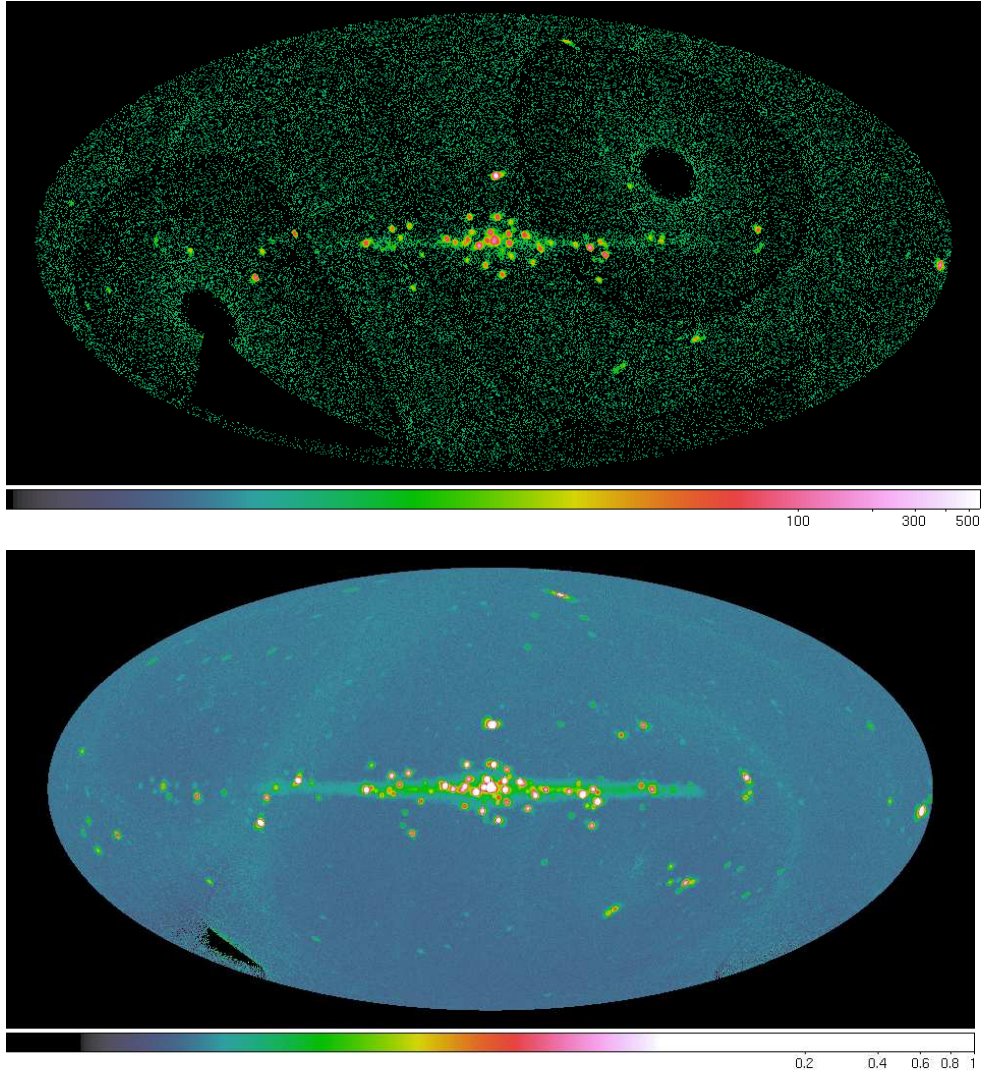
First, we investigate the detectability of the GSC. Figure 9 illustrates one-orbit and one-week observations. The results indicate that we can detect a 20 mCrab source in one-orbit at a confidence level of 5-sigma, and a 2 mCrab source in one-week at a level of 5-sigma. These simulations are estimated for the energy band of 2-30 keV of the Crab nebula spectrum. This simulation is ideal, because the particle and intrinsic background of 10 counts  $\text{sec}^{-1}\text{counter}^{-1}$  is steady, except for statistical fluctuation during the observation time, and this background is subtracted with statistical fluctuation from integrated events of the source. The spectrum of an intrinsic background is



**Fig. 10.** Simulated spectra of Crab nebula for one-orbit (lower spectrum) and one-day (upper one) observations.

referred to the laboratory test result. In reality, we must consider the changeable background on the ISS orbit and systematic errors for attitude determination and response functions. The final detectability could be 0.2 mCrab for a two-year observation, which means a source confusion limit for the angular resolution of 1.5 degrees.

Here it is noted again that the above 5-sigma detectability is under the best condition for known source. The detectability depends on the intrinsic background or trapped particle background. Either of zenithal and horizontal cameras can observe most directional sources even if the



**Fig. 11.** An all-sky X-ray source image (raw data) simulated for one-orbit observation (upper panel) and an image (exposure corrected) for one-month (lower panel) on the Galactic coordinate. The undetected (dark) region on the left bottom corresponds to the solar direction. The two circular dark regions on the upper panel correspond to unobservable regions around both end directions of ISS pitch axis.

ISS passes through the SAA. This makes the detectability uniform for most direction except the direction around the Sun if observations are repeated by orbits. In fact, a deviation from uniformity of the detectability of one orbit becomes worse by about 65 % for the sources observed on the SAA path, while that of one day becomes uniform within 10-20 % for any direction except the solar region. We evaluated another detectability excluding observation in the region less than the cut-off rigidity of 8 (e.g., aurora region). A situation of this detectability is not so much different from that of the aforementioned detectability. Lastly, it is noted that a detectability for unknown source is not significantly different from that for known sources. One-sigma location error for unknown 5-sigma sources is about 0.2 degrees for both one day and one week observations.

Second, we perform a simulation to derive the energy

spectra of a source of 1 Crab for a one-orbit and a one-day observation as shown in Figure 10. This simulation is also ideal, because the background is steady only with statistical fluctuation and ideal determination of the attitude without an unknown systematic error is assumed. Nevertheless, it is concluded that reasonable spectra from a considerable number of sources are obtained by MAXI.

Another important goal of MAXI is to make X-ray source catalogues for every period of concern. We can make light curves with the time bin for various X-ray sources. The light curves of most Galactic X-ray sources are obtained with time bins of one orbit or one day. If the time bin is one month, it is possible to make light curves of a considerable number of AGNs brighter than 1 mCrab as shown on the lower panel in Figure 11. It is not easy at a glance to discriminate between the weak sources and the CXB, but 1-2 mCrab sources are significantly detected as

simulated in Figure 9 (b). If we integrate all event data from the sky for two years, we can create an X-ray source catalogue brighter than 0.2 mCrab at a confidence level of 5-sigma. In general, since the time scale of variability of AGNs is longer than that of Galactic sources, catalogues with time bins of one month and one year will provide new information about long-term variable sources such as the super massive Binary Black Hole (BBH). Actually, an all-sky image for every six-month observation is compatible with the result of HEAO-1 A2.

## 6. Concluding Remarks

MAXI is the first payload to be attached to JEM-EF (Kibo-EF) of the ISS. It consists of two kinds of X-ray cameras: the Gas Slit Camera (GSC), which has one-dimensional position sensitive gas-proportional counters with a 2 to 30 keV X-rays energy band, and the Solid-state Slit Camera (SSC), which has X-ray CCDs with a 0.5 to 12 keV X-rays energy band. MAXI provides an all-sky X-ray image acquisition capability under the best conditions for every ISS orbit. If MAXI scans the sky for one week, it could make 2 mCrab X-ray all sky image excluding the bright region around the Sun. Thus, MAXI not only rapidly informs astronomers worldwide about X-ray novae and transients if they occur, but also observes long-term variability of Galactic and extra-Galactic X-ray sources. At the same time, MAXI provides an X-ray source catalogues accumulated for various periods such as six months, one and more years.

All MAXI instruments are ready for launch. Data processing and analysis software, including an alert system on the ground, are being developed by the mission team. MAXI will be attached to JEM(Kibo)-EF in mid-2009. Anyone can participate in follow-up or multi-wavelength observations of MAXI objects with ground optical and radio telescopes, and at space observatories. Please contact the present authors for more information and further collaboration.

Finally, please refer to the Proceedings of Astrophysics with All-Sky X-Ray Observations – 3rd International MAXI Workshop –, RIKEN, Wako, Japan, June 10-12, 2008, ed., N.Kawai, T.Mihara, M.Kohama and M.Suzuki (<http://cosmic.riken.jp/maxi/astrows/>) for further information on MAXI instrumentations and preliminary guideline for MAXI data.

MAXI fabrication and testing are also supported by the staffs at the JEM project office and the Space utilization office. We thank them for their valuable guidance and co-operation in maximizing the scientific output from MAXI. We also thank the former colleagues who developed and supported this long-term project of MAXI, although these many colleagues (staffs and graduate students) have not been included as co-authors.

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for the gas proportional counters, Hamamatsu Photonics K.K. for the CCDs, ATK Space (former Co.: Swales Aerospace) for the LHPRS, DTU (Technical University of Denmark) for the Optical Star Sensor, the Institute of Aerospace Technology in JAXA for the GPS, and other cooperating companies and institutions.

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